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Spatial pattern formation of optically excited carriers in photoconductive THz antennas

M. Bieler, G. Hein, K. Pierz, U. Siegner, M. Koch, M. W. Feise, D. S. Citrin

Abstract –
We have investigated the role of spatio-temporal carrier dynamics in photoconductive THz antennas. To this end, the photoluminescence from a GaAs/AlGaAs quantum well has been spatially resolved after femtosecond laser excitation for different electric bias fields applied in the plane of the well. The photoluminescence patterns demonstrate substantially different electron-hole dynamics across the excitation laser spot. The density dependence of screening combines with the lateral variation of the carrier density to produce the observed effects. The experimental data are compared to a self-consistent calculation of the drift-diffusion equation for electrons and holes and Poisson's equation for the electric field in both space and time. Our results prove that the spatial variation of the carrier dynamics should be taken into account for further optimization of THz antennas.

I. Introduction

Photoconductive dipole antennas are widely used to generate pulsed THz radiation [1]. These semiconductor antennas basically consist of a piece of semiconductor onto which coplanar metallic microstriplines are deposited. An ultrashort laser pulse injects carriers into the semiconductor gap between the metallic electrodes. An applied bias field accelerates electrons and holes towards the electrodes. The resulting photocurrent gives rise to the emission of a THz pulse.

Considerable experimental effort has been made to optimize photoconductive dipole antennas for THz power and bandwidth [2]. Moreover, the temporal evolution of the photocurrent was numerically modeled by a Drude-Lorentz approach [3]. Although this model describes the experimental results quite well, one fundamental problem has not been addressed so far, namely the *spatio*-temporal dynamics of the optically created carriers. It is obvious that the field-induced motion of all optically excited electrons and holes determines the shape of the current pulse and thus the THz bandwith.

The carrier motion is determined by the local field which, in turn, is constantly modified by screening resulting from the carrier displacement. Due to the non-uniformity of the Gaussian excitation spot, we can expect different carrier dynamics in its center and at its edges. Since the carrier density is lower at the edges, electrons and holes have to separate further in order to screen the bias field. As these carriers have to move a larger distance, it can be expected that their contribution to the total current persists for a longer time as compared to the current contribution resulting from the carriers in the center of the excitation spot (see schematic drawing in Fig. 1). The shape of the current pulse is given by the integral of all partial currents.

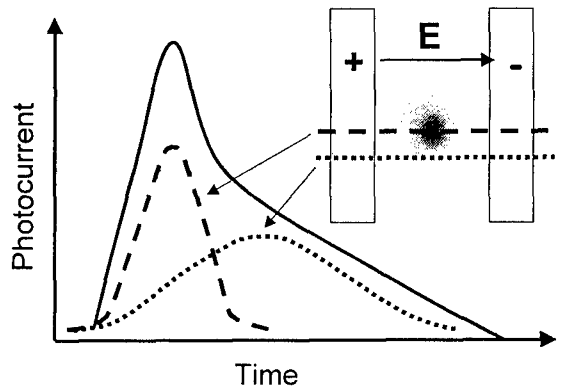

Fig. 1: Schematic of the photocurrent pulse.

In this paper, we address the complex problem of the spatio-temporal pattern formation in an optically excited photoconductive THz antenna. We have performed temporally integrated but spatially resolved luminescence experiments on a biased semiconductor. The results are compared to numerical solutions of the drift-diffusion equation. The comparison confirms that the carrier dynamics spatially varies over the excitation spot and yields first quantitative information on the spatio-temporal carrier dynamics.

II. Experiment

The sample consists of 30 GaAs/AlGaAs quantum wells with a thickness of 12 nm. It is excited with 150 fs Ti:sapphire laser pulses at 800 nm. The full width at half maximum of the focused laser spot, which is centered between two Ni-Au/Ge-Ni electrodes (see inset of Fig. 2), is approximately 25 μm. The luminescence, which peaks at 860 nm, is imaged onto a two dimensional charged coupled device (CCD). In front of the CCD camera an interference filter is introduced to suppress reflected pump light. The spatial resolution of our setup is close to the diffraction limit. All experiments are carried out at room temperature.

Without field, we observe a Gaussian luminescence spot following the Gaussian intensity profile of the laser beam. When an electric field is applied, the overall luminescence intensity drops [4], the luminescence profile becomes narrower and the position of the peak is slightly displaced towards the anode [5]. These effects result from the motion of the electrons towards the anode

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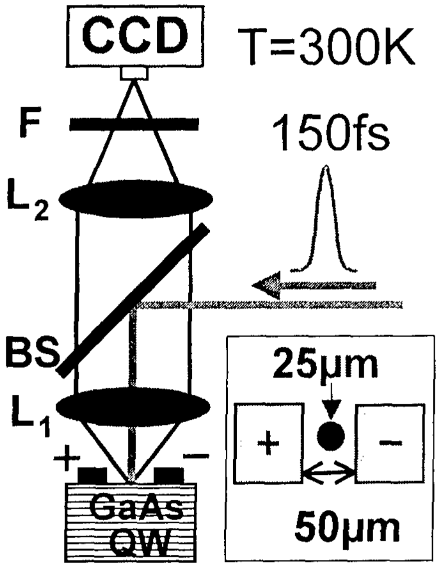

Fig. 2: Experimental setup. BS: beam splitter; F: interference filter; L1, L2: lenses; CCD: charged coupled devive. The inset shows the ohmic Ni-Au/Ge-Ni contacts.

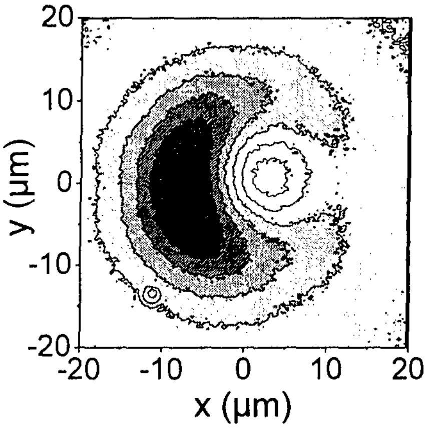

Fig. 3: Normalized luminescence without field minus normalized luminescence with field (differential luminescence) shown as a contour plot. The bias field is 4 kV/cm and the spatially averaged carrier density is about 7 x 10^{11} cm^{-2}.

while the holes hardly move. The effect of the field induced carrier motion is visualized most clearly when plotting the normalized luminescence pattern with electric field subtracted from the normalized luminescence pattern without field. This "differential luminescence" pattern is shown in Fig. 3 for a bias field of 4 kV/cm and a spatially averaged carrier density of 7x10^{11}cm^{-2}. The field is applied in x-direction and the anode is on the right-hand side. The center of the excitation laser spot is at (0,0). Dark colors mark a strong field-induced reduction of the luminescence (white: enhancement of the normalized luminescence). Zero is indicated by the grey tone in the lower left corner of the contour plots.

In all experiments, even with lower excitation densities, we observe a characteristic crescent-shaped pattern. When increasing the electric field from 1 to 4 kV/cm the crescent becomes more pronounced and almost encircles the white region. From a comparison with simple analytical expressions [5], we conclude that different carrier dynamics occur in the center and at the edges of the excitation spot. The carrier density dependence of screening is at the origin of this result [5]. In the following we present more elaborate numerical calculations.

III. CALCULATION

We describe the motion of the charge carriers in the framework of the drift-diffusion model [6]. The carriers are represented as 2-dimensional densities of electrons and holes located in a single GaAs quantum well. Scattering processes and the band structure of the material are approximated by an effective mobility and diffusion coefficient. The equation of motion for the charge carriers reads:

$$\frac{\partial f_{h,e}}{\partial t} = D_{h,e}\nabla^2_{x,y} f_{h,e} \mp \mu_{h,e}\nabla_{x,y}\cdot(f_{h,e}\vec{E}) + \frac{(G-R)}{e}$$

Here f is the particle density, D the diffusion coefficient, μ the carrier mobility, and e the elementary charge. Moreover, E is the local electric field that consists of the uniform external field and the screening field. The latter is self-consistently determined through Poisson's equation. G is the position and time dependent generation term that describes the electron-hole pair creation by the laser pulse. The band-band recombination of electrons and holes is given by $R=rf_hf_e$ where r is the recombination coefficient. This recombination term leads to a non-exponential decay of the charge carriers and does not allow the definition of a constant recombination time [7].

We solve the equation using a finite difference technique [8]. The motion of the charges is constrained to the plane of the quantum well whereas the electric field is calculated in three dimensions. We assume the following boundary conditions: (i) No charge carriers are injected into the quantum well by the applied voltage. (ii) Carriers in the quantum well can enter the electrodes and then no longer contribute to screening of the external field. (iii) In the direction normal to the external field, where no electrodes provide a boundary for the carriers, we extend the computational region far enough to ensure that the numerical boundaries have only negligible influence on the results.

To solve Poisson's equation, one can first treat the direction normal to the quantum well analytically and then solve for the potential in the plane of the quantum well self-consistently at each time step. The electrodes are assumed to be held at a constant potential. In this approach, the voltage change induced by the moving free charges in the quantum well is compensated by the voltage source. In the in-plane direction normal to the external field, we extend the calculation until the

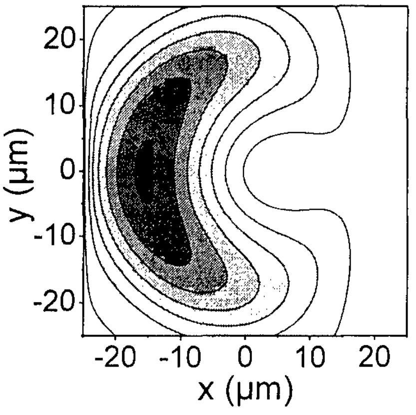

Fig. 4: Calculated differential luminescence for a bias field of 4 kV/cm and a carrier density of 3×10^{11} cm^{-2}. The integration time and the recombination coefficient are 24 ns and 5×10^{-3} cm^2/Vs, respectively. The electron and hole mobilities are 100 cm^2/Vs and 5cm^2/Vs, respectively. Temperature 300 K.

potential is close to the value of the potential with no net charge in the computational region.

Figure 4 shows the calculated differential luminescence for parameters comparable to the experiment; see caption for details. The characteristic crescent-shaped pattern is well reproduced by the drift-diffusion model.

IV. CONCLUSION

In summary, we have performed luminescence experiments on a photoconductive THz antenna. The experimental results demonstrate different carrier dynamics at the center and the edges of the excitation spot. The results are in qualitative agreement with first numerical calculations based on the drift-diffusion equation. The comparison between experiment and theory can provide quantitative information on carrier dynamics. This information provides the basis for the further optimization of photoconductive THz antennas taking into account spatial effects.

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